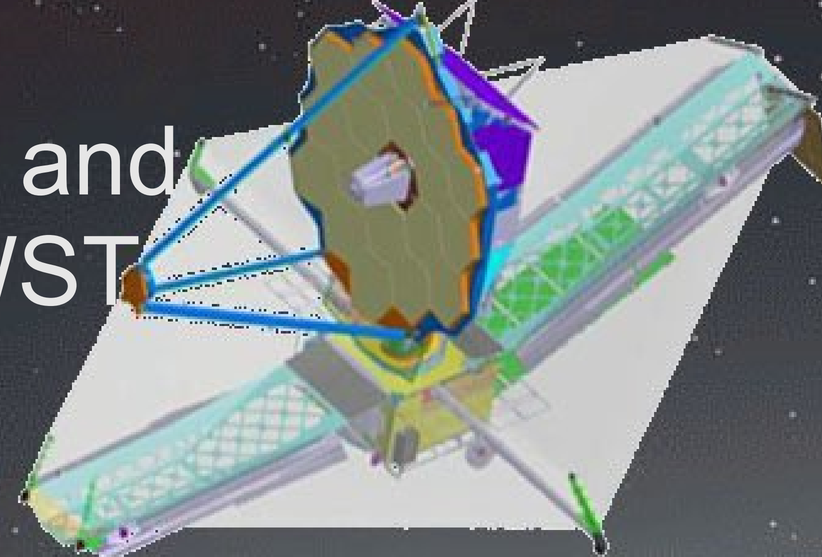
Simulating Exoplanet Transit and Eclipse observations with JWST



Tom Greene (NASA ARC)

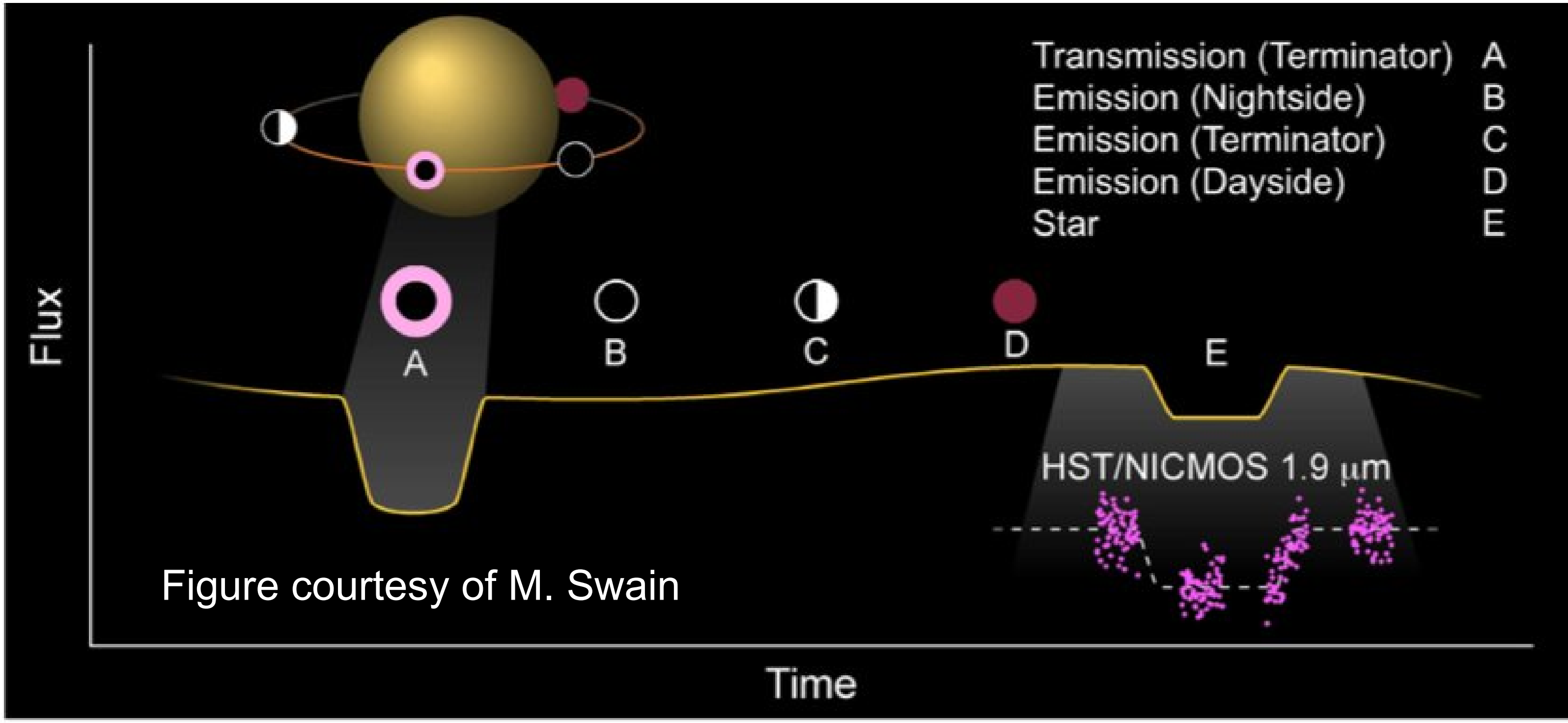
IPAC & JPL visits

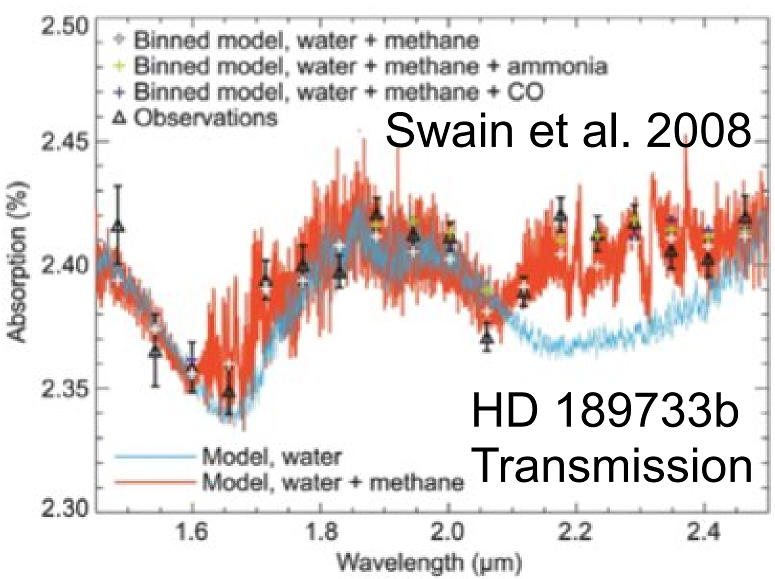
Sep. 28/29, 2011

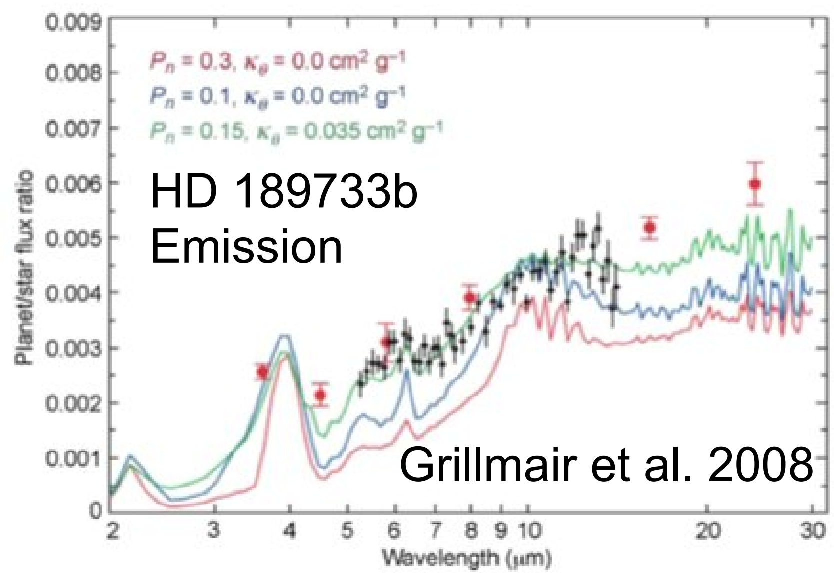
Scope of Talk

- Exoplanet Time Domain Spectroscopy
- Outstanding Science Issues
- How Can JWST Help?
- Optimum Targets
- Planet Models
- Systematic Errors
- Simulated Spectra and Potential Science
- Other related missions
- Takeaways

Exoplanet Spectroscopy Status

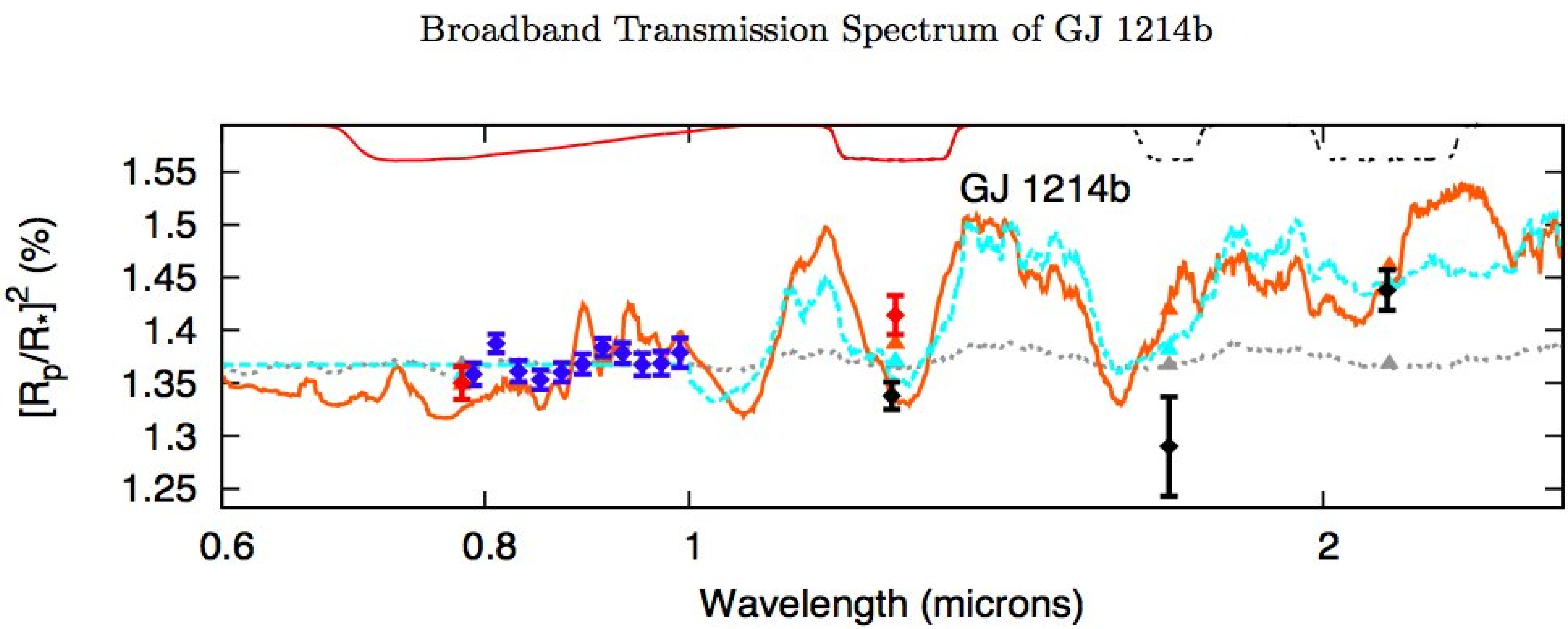




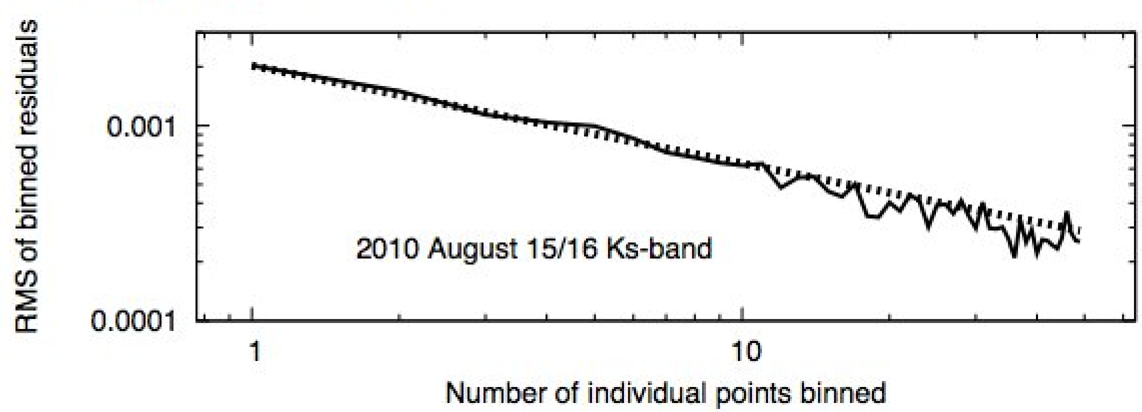


Exoplanet Spectroscopy: The Ground

- The ground is trying. Enough aperture but control of systematic noise is difficult.



- B. Croll et al. 2011 photometry (black), Bean et al. (blue), Mearth+KPNO (red)
- Swain and others doing spectroscopy
  - lots of work with IRTF and Keck

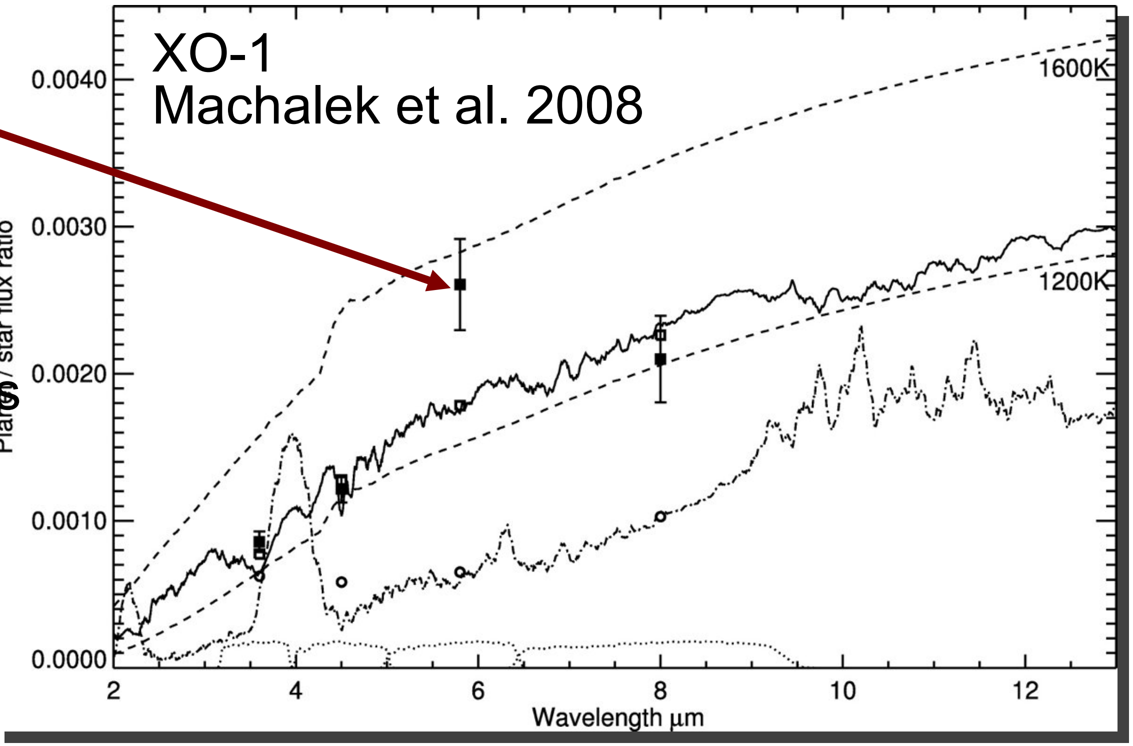


Some Outstanding Issues

- What spectral features are really present?
- Are observed strengths of spectral features due to abundances or temperature profiles?
  - Distinguish temperatures, T profiles, compositions
  - Are ice giants overabundant in carbon like Neptune?
- How is energy absorbed and transported in highly irradiated planets?
  - Measure & determine causes of temperature inversions
  - Study transport via day / night side differences
- Is there non-equilibrium chemistry at work?
  - Hydrocarbons like C_2H_2 (acetylene), C_2H_6 (ethane) indicate photo-chemical production
- What is the composition of mini-Neptune atmospheres?
- Can we detect any features in Super-Earth atmospheres?

Unidentified features in high insolation

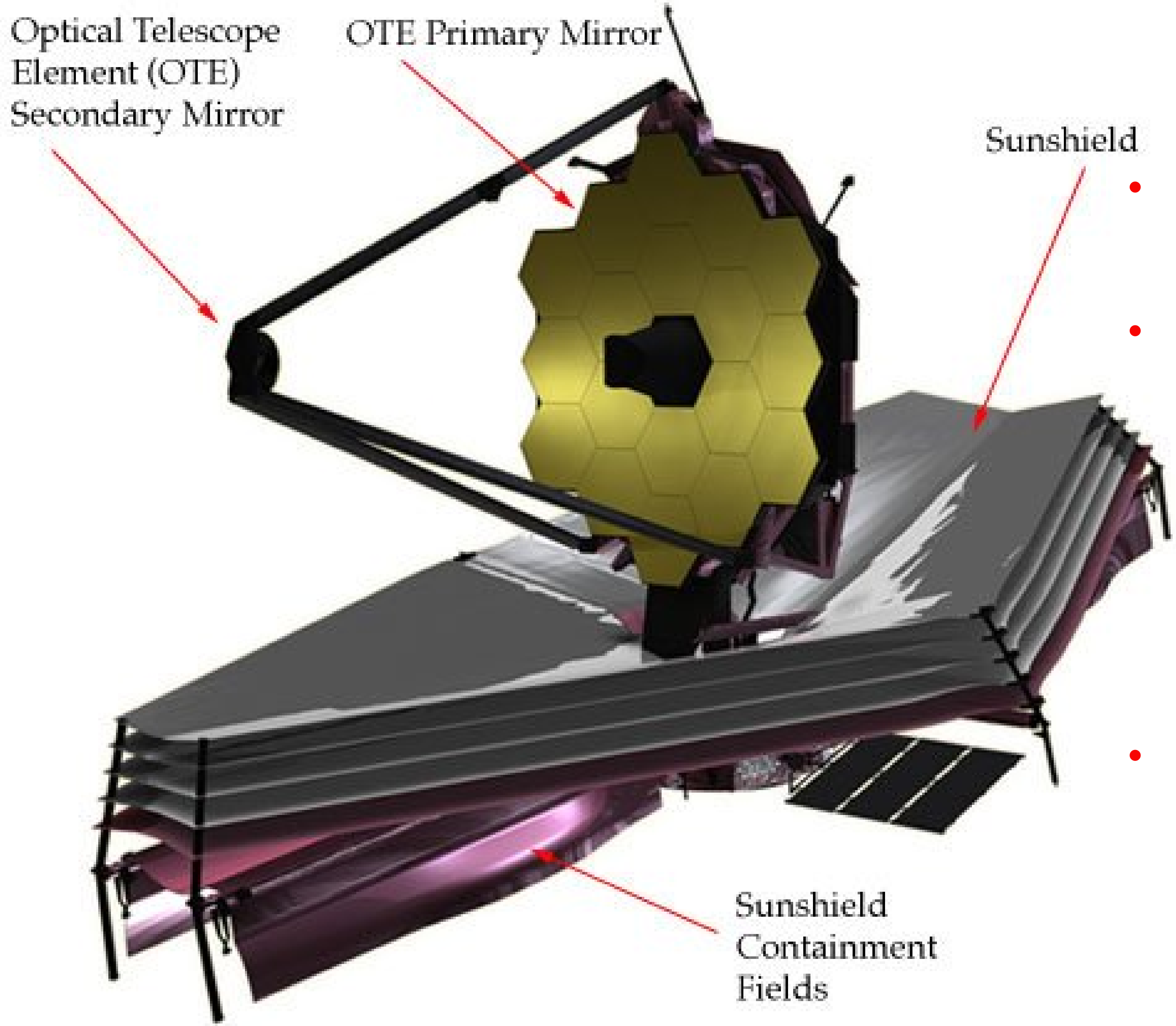
- Excess Spitzer IRAC Band 3 emission seen in exoplanets with hot stratospheres / high altitude inversions like HD 209458 b
- Common to several planets, most highly insolated
- Is it enhanced continuum or an unknown spectral feature
  - Current models can't fit it with continuum or a species (TiO / VO tried & non-equiib processes suggested)
  - Useful in understanding energy transport in atmosphere and compositions of planets



Conundrum

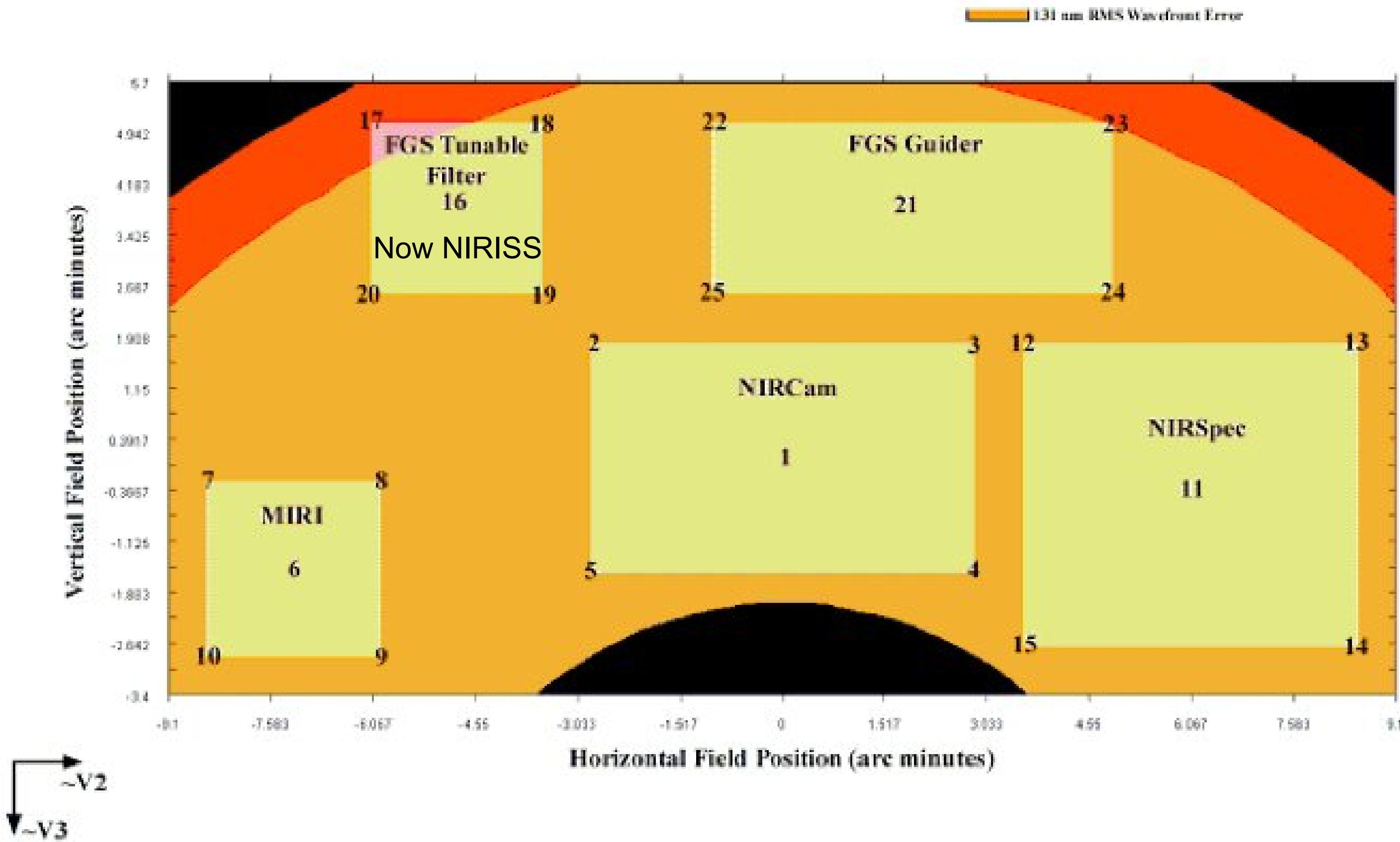
- Current spectroscopic data are pretty marginal, even for the best / most favorable planets
- We really need good red-to-IR spectra for studying the molecular features in atmospheres of planets around M stars
  - HST is limited in aperture, stability, and wavelength coverage
- Q: How do we get more and better data?
  - A: JWST (hopefully)

JWST in a nutshell



- 6.5-m primary mirror; 18 segments.
  - T~40K, bkg. limited
- λ <1 - 28 μm
  - zodi-limited to 10μm
- Instruments:
  - NIRCam 1 – 5 μm
  - NIRSpec 1 – 5 um
  - MIRI 5 – 28 um (cam + spec)
  - FGS w/slitless spectrograph 1 – 5 um
- 201X launch
  - Arianne V to L2
  - 5 yr req life
  - 10 yr goal
  - No cryogens

Focal Plane Layout



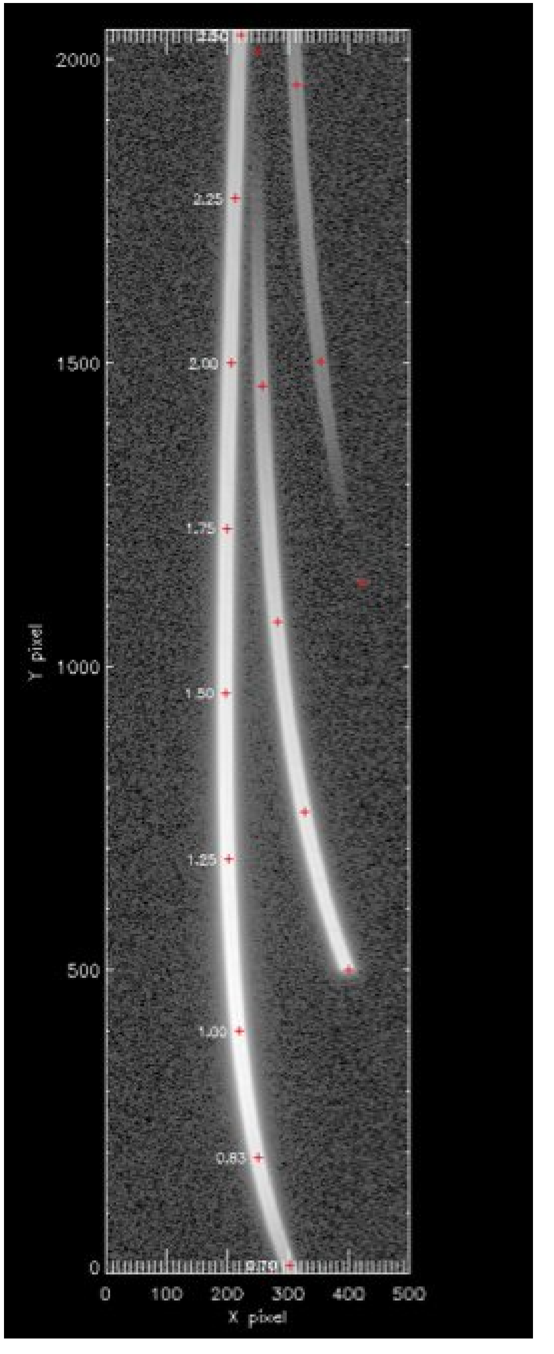
- Instruments view different parts of JWST focal plane
- Little parallel operation currently planned

How Can JWST Help?

- JWST has 6.5 m aperture vs. 2.4 m for HST and 0.85 m for Spitzer
  - Photon noise-limited SNR goes as aperture size, so JWST should be capable of SNR ~ 3 – 8 times present values
- JWST has great spectroscopic capabilities, particularly:
  - λ = 0.7 – 5 μm, R ~ 100 mode with NIRSpec prism
  - λ = 0.7 – 2.5 μm, R ~ 700 mode with NIRISS grism+prism (slitless)
  - λ = 2.5 – 5 μm, R ~ 1700 mode with NIRCam grisms (slitless)
  - λ = 5 – 12+ μm, R ~ 70 mode with MIRI LRS prisms (slitless)
- JWST is being designed and will be operated to maximize exoplanet spectroscopy SNR
  - Wide NIRSpec slit (1400 mas) and slitless mid-IR spectroscopy
  - Testing spectrophotometric precision and simulating operations
  - Systematic noise due to pixel size and observatory parameters are being modeled (P. Deroo PASP submitted), mitigation possible

New NIRISS "Exoplanet grism"

- R = 700 grism covers 0.7 – 2.5 μm
- Cross-disperser prism allows entire wavelength coverage at once
- Cylindrical surface on prism provides WFE in X-dispersed axis only. More pixels provide:
  - Less systematic error
  - Brighter saturation limit



JWST Observational Constraints

- JWST instantaneous field of regard is limited
  - Sun angles between 85 and 135 degrees (35% of sky)
  - Two 50-day visibility windows per year near ecliptic
- JWST is optimized for long exposures of faint objects but subarrays do provide reasonable bright limits:
  - K ~ 5-8.5 mag for R=700 NIRISS grism (0.7/0.9 – 2.5 μm)
  - K ~ 5 mag for R=1700 NIRCam grism (2.4 – 5 μm)
  - K ~ 7 mag for NIRSpec R ~ 33 – 315 prism (0.7 – 5 μm)
  - Low overhead for long sequence of identical integrations if not too bright
- Ground bright limits are similar for R ~ 20,000 Keck
  - Narrow-band imaging could have similar limits if subarrays used

What are the optimum JWST targets?

- Ideally we need planets transiting / eclipsing IR bright nearby but small stars
  - Star SNR ~ sqrt(Signal) and transit depth ~ $(R_{pl} / R_*)^2$
  - M stars are ideal if stable
  - Kepler planets are too faint / distant for spectroscopy
- Planets with large atmospheric scale heights $kT/(\mu g)$ will have relatively high SNR spectra
  - Gas giants, ice giants, mini-Neptunes will be good
- Impossible to detect atmospheric features in true Earth / Sun analog
- ***We need an all-sky transit survey mission to find good planets:*** ELEKTRA (or TESS) Explorer

Selecting some good existing targets

Identify known transiting planets with interesting properties, Estimate transit and eclipse spectroscopy SNRs (fluxes, radii, Teff, densities), then collect their red-to-mid-IR models for spectral simulations

- HD 189733 - No inversion, insolation hot spot, bright star
- WASP-18b - High mass, high log g, short period, high insolation
- HD 209458b - Thermal inversion, high insolation, high SNR
- WASP-12b - Large radius, low log g, disrupting?
- TrES-3b - Short orbital period
- HD 80606b - Extreme eccentricity, large insolation range
- WASP-17b - Large radius, huge scale height
- GJ 436b - Neptune-sized, M star host
- GJ1214b - Small size, cool, M star host (MIRI thermal)

Planet Models (J. Fortney & Collaborators)

- “Hot Jupiters”, “Neptunes”, “mini-Neptunes”
- Absorption and Emission models
- Variations for re-radiation geometry (2 pi / 4 pi), abundances, chemistry

Planet	Star SpT	V* (mag)	R* (Rsun)	R_pl (Rj)	t_trans (m)	t_ecl(m)
HD 189733b	K1.5	7.7	0.79	1.15	110	110
HD 209458b	G0V	7.7	1.15	1.38	144	144
HD8606b	G5	8.9	0.98	0.92	728	101
TrES-3	G	12.4	0.81	1.31	78	78
WASP-12b	G0V	11.7	1.57	1.79	162	162
WASP-17b	F6	11.6	1.38	1.74	262	262
WASP-18b	F9	9.3	1.23	1.17	135	135
GJ 436b	M2.5V	10.7	0.46	0.37	60	60
GJ1214b	M4.5V	14.7	0.21	0.24	50	50

Warning!

- Never trust anybody who simulates data for unbuilt future observatories!

JWST Simulations

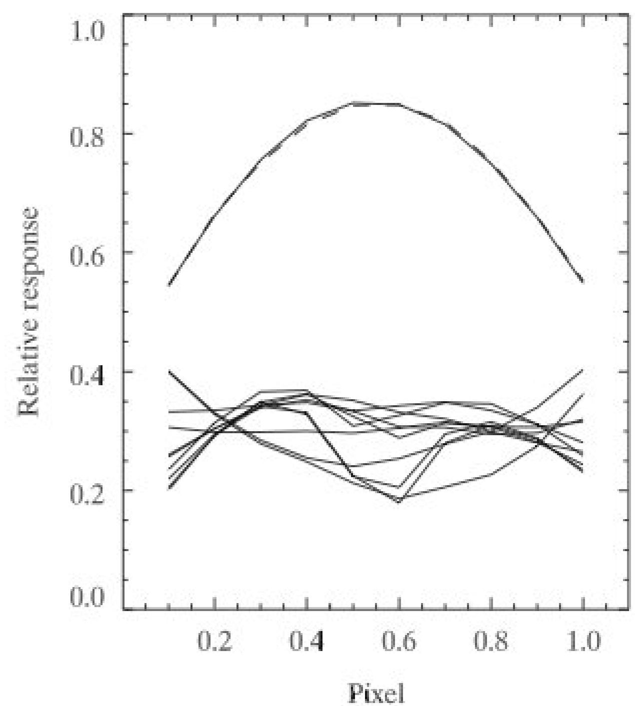
- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
  - Includes reflections, grating functions, filters
  - Use actual instrument models or guesstimates
- Photon noise and systematic noise added
- Systematic noise is difficult to predict but starting to model it
  - Different for each instrument and mode
  - May have large wavelength dependencies (Deroo sub. PASP)
- Compare simulations of model variants to determine what science issues can be addressed with JWST data

JWST Systematic Noise Estimates

- Variable PSF and image jitter will induce spectrophotometric errors due to non-uniform intra-pixel detector response and residual flat field errors
- These effects were noted in the Spitzer IRAC InSb detectors and calibrated out to about 1E-4 precision
- Use of slitless spectrographs and JWST NIRSpec wide slit (1600 mas) will eliminate any systematic noise due to jitter-induced slit losses

Deming et al. 2009 PASP

FIG. 8.—Intrapixel sensitivity variation for a representative NIRSpec detector pixel, from engineering measurements of the flight detector. The upper traces show the average variation in the dispersion direction (*solid line*), and the spatial direction (*dashed line*). The lower traces divide the pixel into 10 strips parallel to the spectral dispersion, and they show the difference from a parabolic fit of response vs. distance from pixel center. The differences have been amplified by a factor of 4, and offset by 0.3, for clarity of presentation.



Impact of Pointing Oscillations

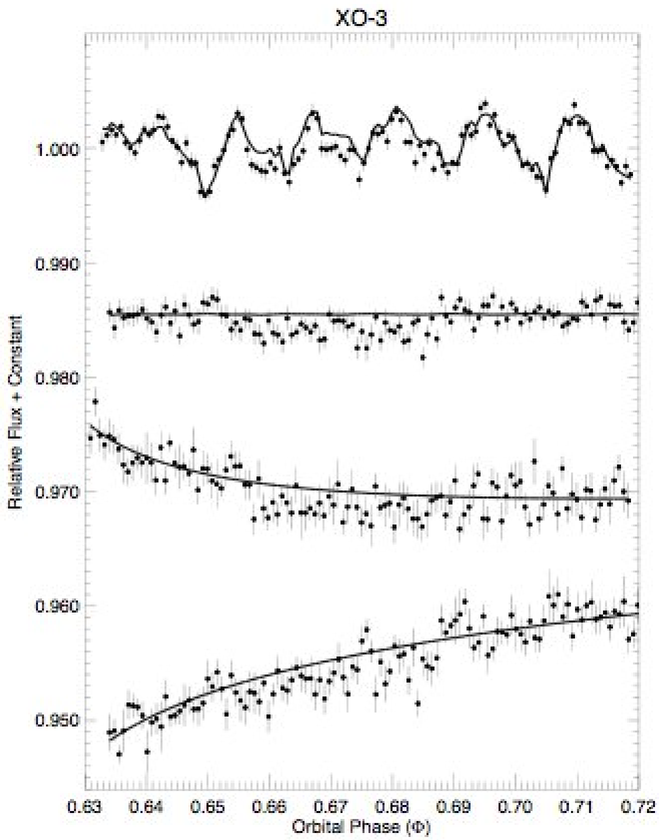


Fig. 3.— (left) Secondary eclipse observations of XO-3 with IRAC on *Spitzer Space Telescope* in 3.6 micron, 4.5 micron, 5.8 micron and 8.0 micron channels (from top to bottom) binned in 3.5-minute intervals and normalized to 1 and offset for clarity. Note, however, that all our analysis is performed on the unbinned data. The overplotted solid lines show the corrections for the detector effects (see text).

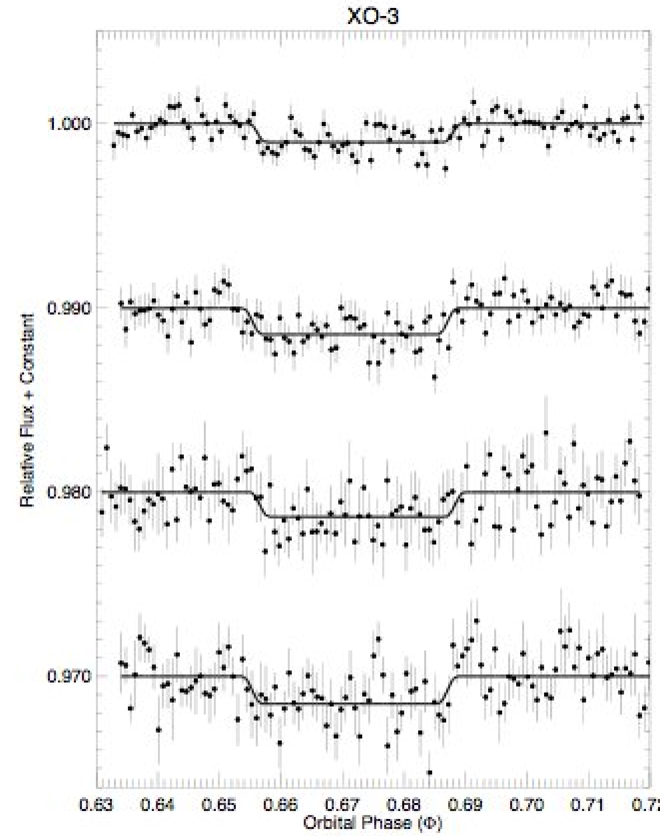
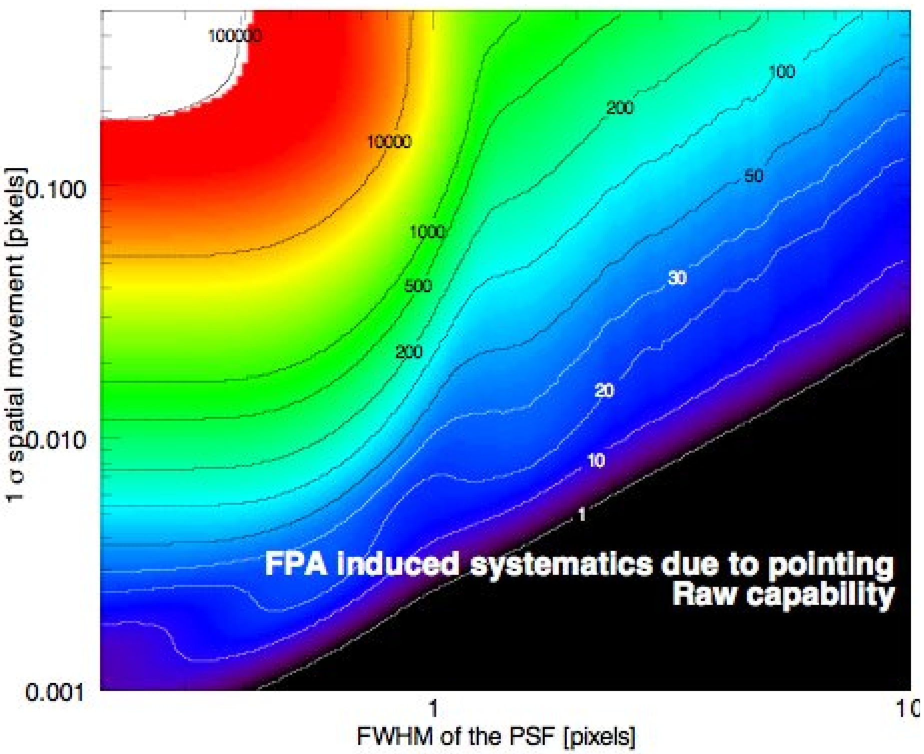


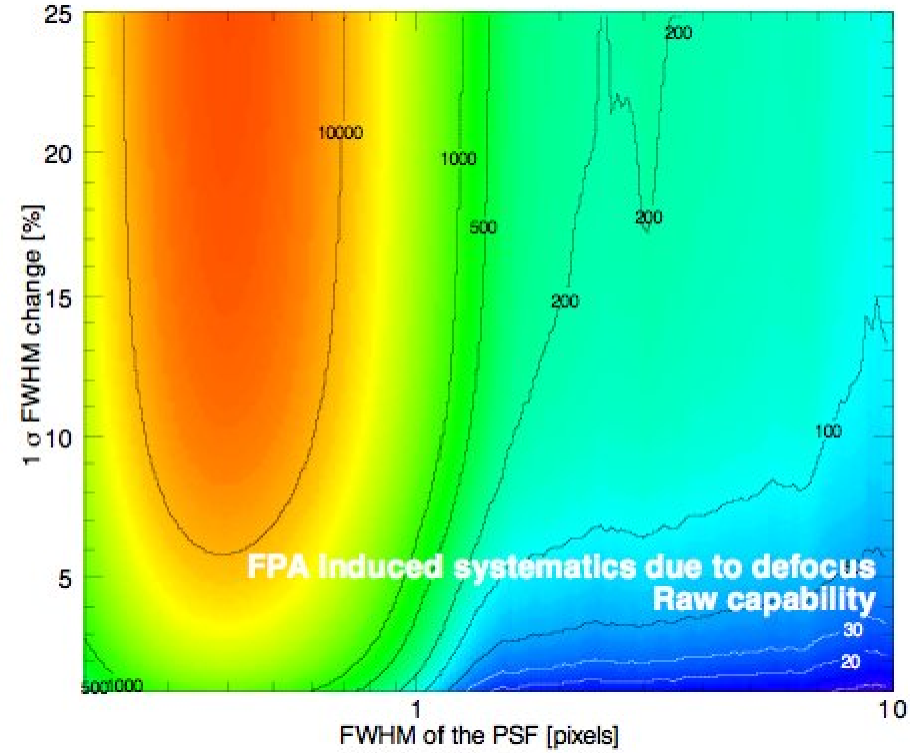
Fig. 4.— Secondary eclipse of XO-3b around the star XO-3 observed with IRAC on *Spitzer Space Telescope* in 3.6, 4.5, 5.8, and 8.0 micron channels (top to bottom) corrected for detector effects, normalized and binned in 3.5-minute intervals and offset for clarity. The best-fit eclipse curves are overplotted. Note, however, that all our analysis is performed on the unbinned data.

- Spiter IRAC transit photometry before (Left) and after (Right) de-correlation with image motion (Machalek et al. 2010)
- 3.6 and 4.5 μm bands (top 2) have variations due to pointing

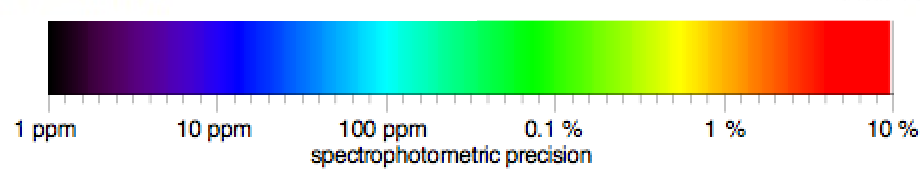
Systematic Noise Estimate Models

- P. Deroo et al. have modeled the impact of pointing drifts, PSF variations (defocus), and slit-induced losses on spectrophotometric precision
- Focus and pointing drifts are likely the biggest impact for JWST NIRSpec due to its undersampled PSF. Most critical below 2.5 or 3 microns.
- NIRISS GR700XD, NIRCam grism, and MIRI LWS all minimal impact



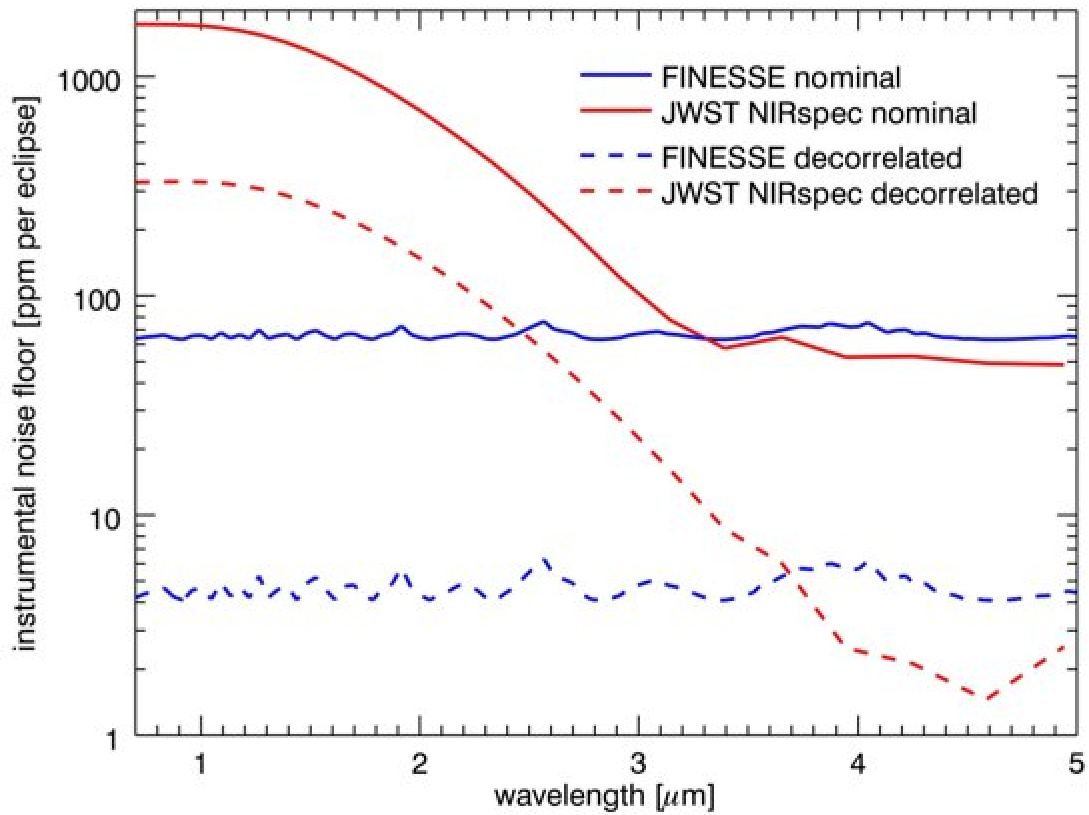


P. Deroo 2011 submitted



Systematic Noise Estimate Models

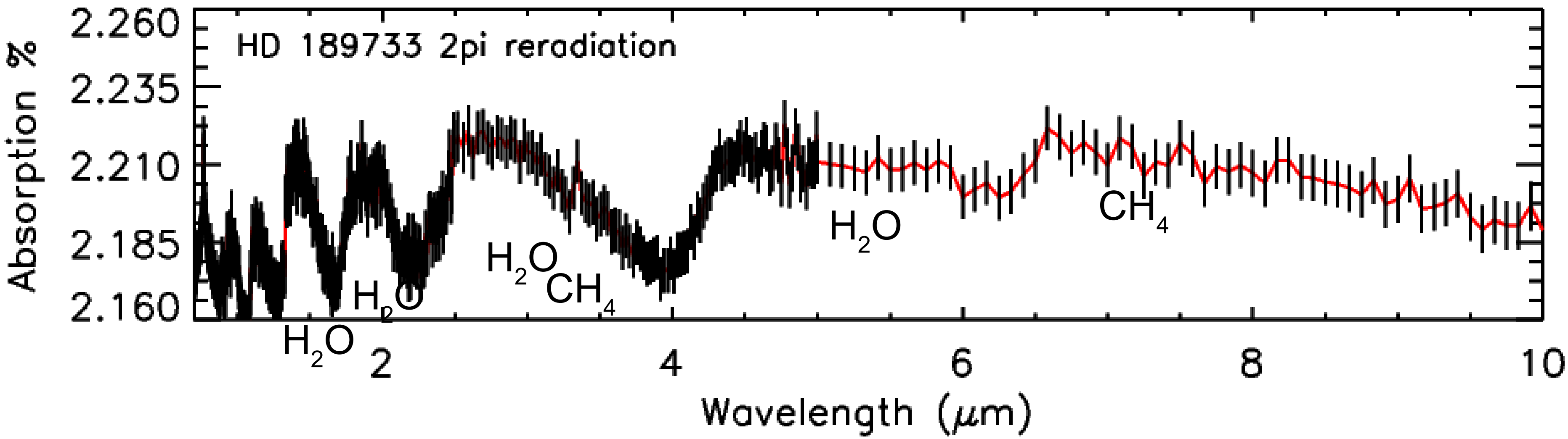
- Even NIRSpec errors can be reduce to better than 1 part in 1E4 with decorrelation. Real-world performance may be better than expected because the NIRSpec PSF is likely to be larger than the JWST telescope PSF.

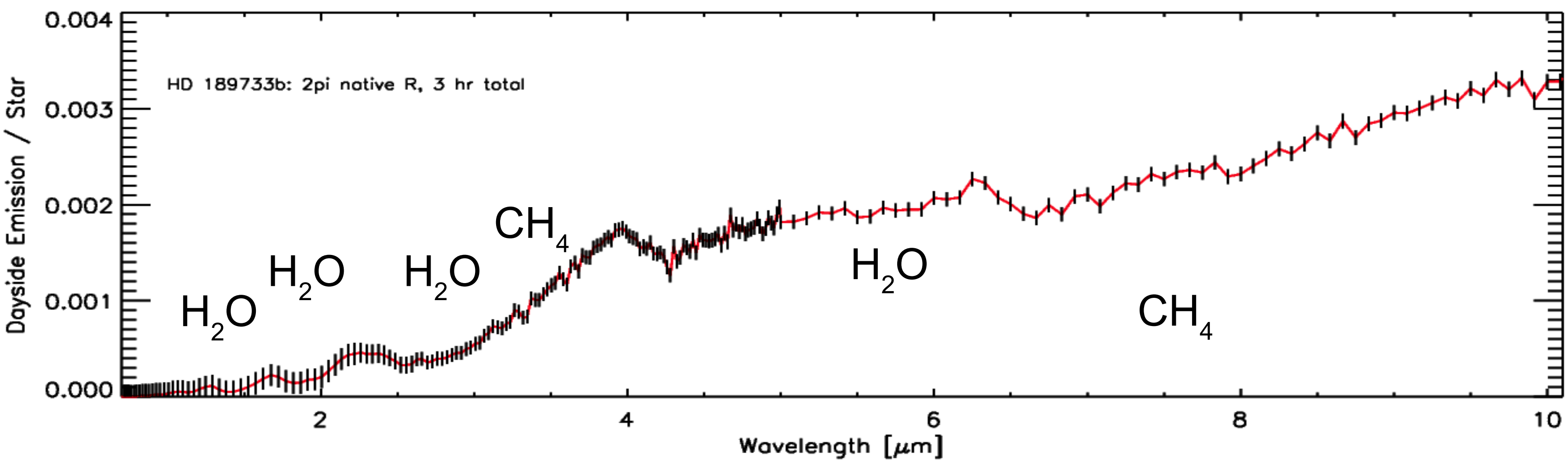


Worst case NIRSpec

Deroo et al. PASP submitted

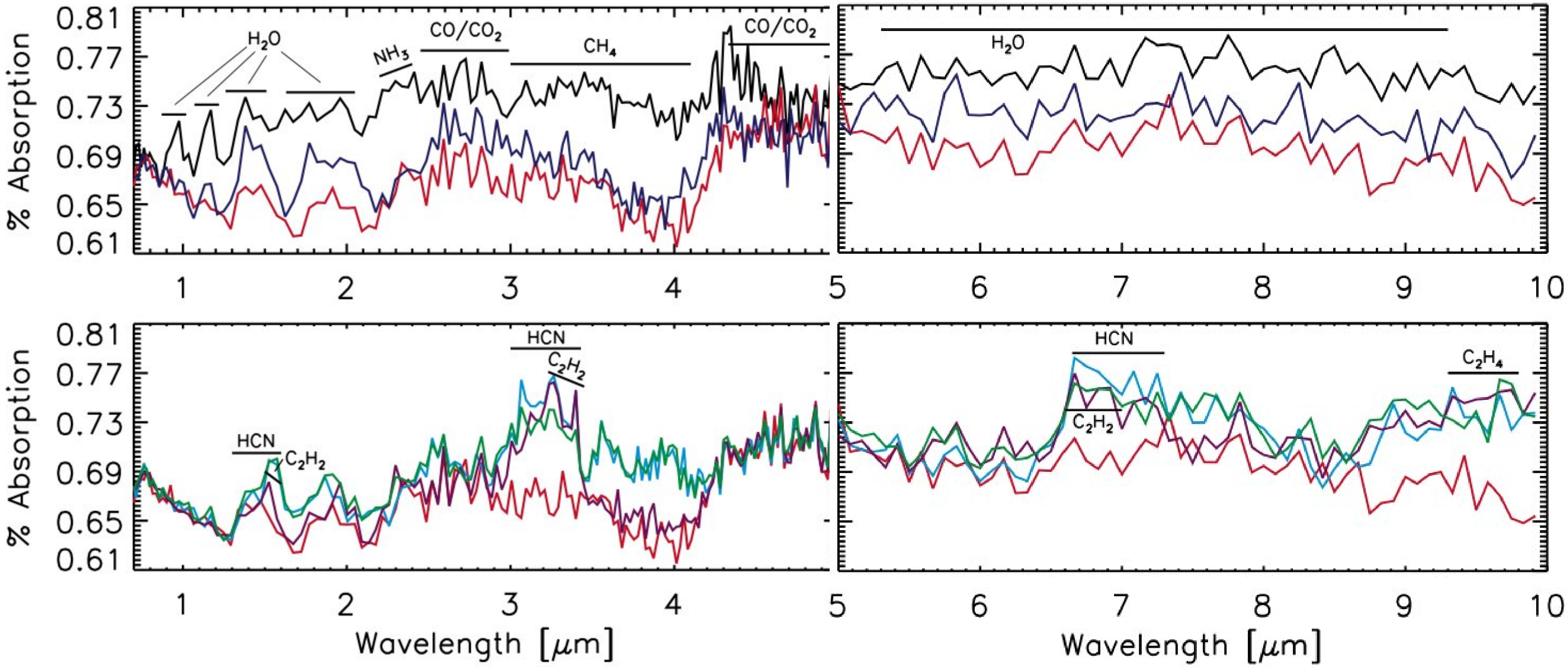
HD 189733b Gas Giant





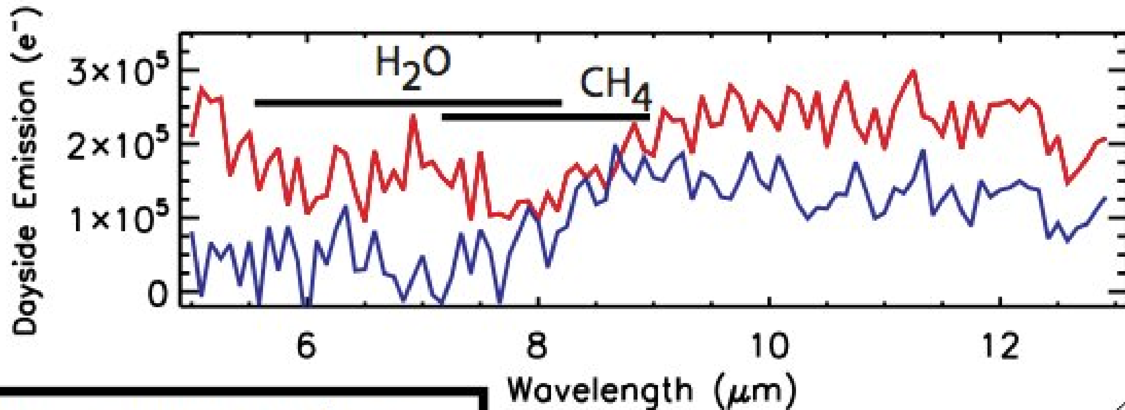
- Only 1 transit (top) or eclipse (bottom) plus time on star for each (1 NIRSPec + 1 MIRI)
- Multiple features of several molecules separate compositions, temperature, and distributions

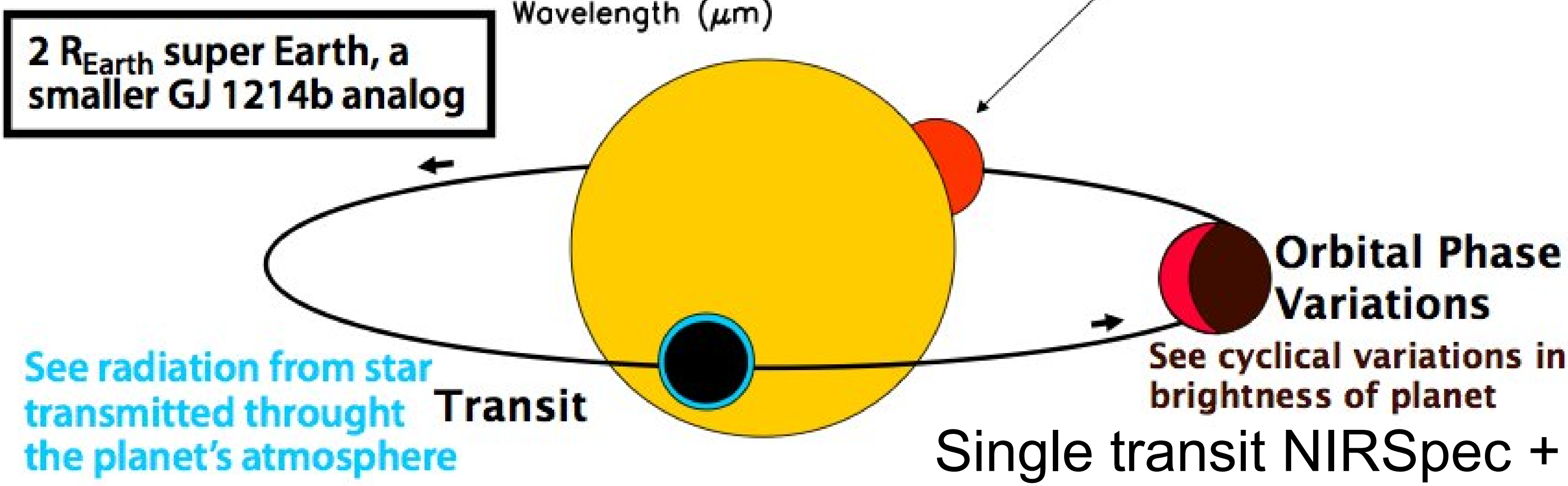
GJ 436b (warm Neptune) transmission spectra simulations



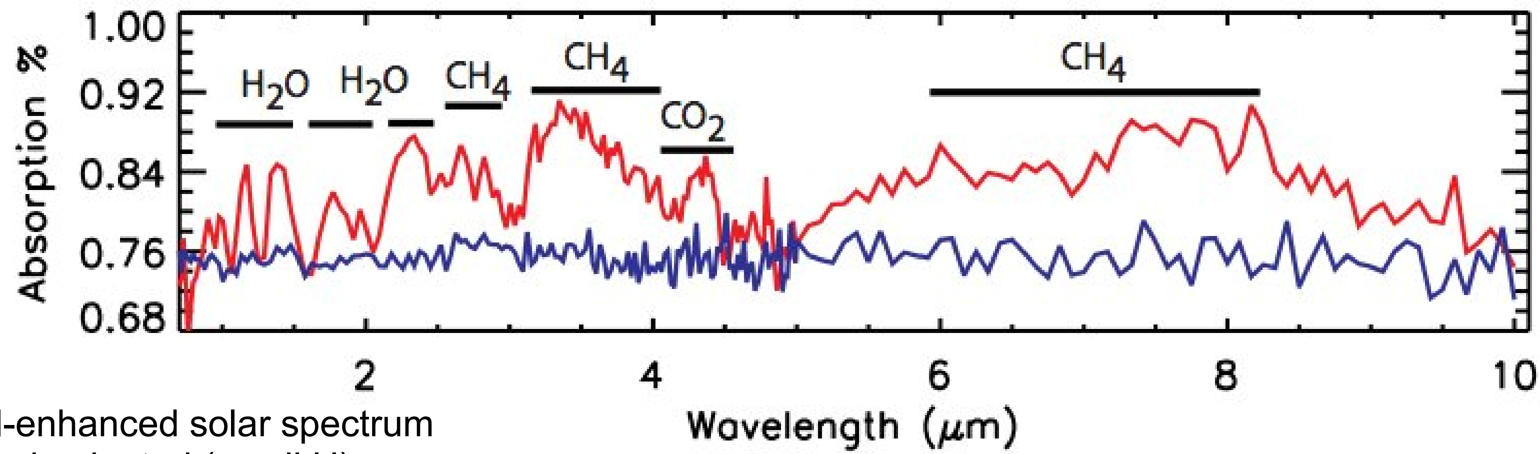
- Simulated single transit model absorption spectra distinguish between equilibrium 30X solar (black), reduced CH4 & H2O (blue, red) or non-equilibrium chemistries where H_2O and CH_4 are absent in favor of higher order hydrocarbons HCN, C_2H_2, and other molecules (purple, cyan and green curves). 1 transit each: 30 min star + 30 min in-transit integration time. Noise has been added (*Shabram et al. 2011)*.

4 MIRI eclipses summed





Single transit NIRSpec + MIRI

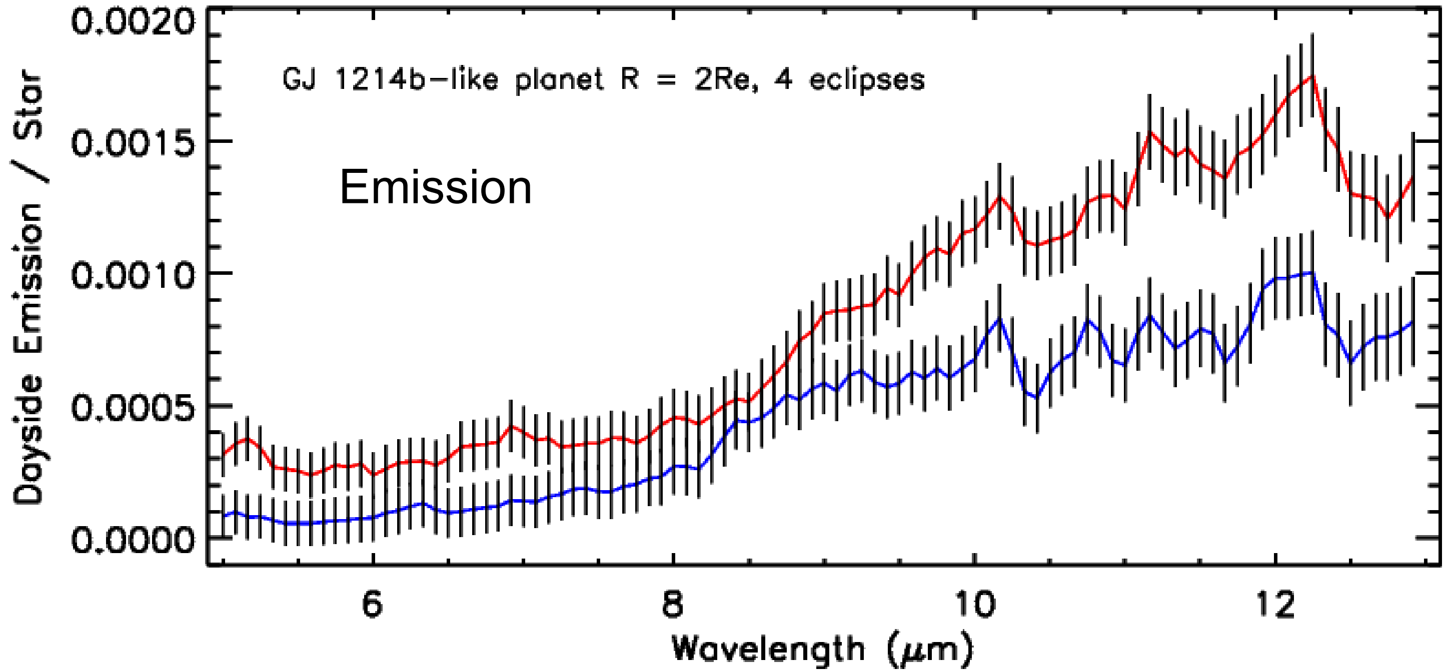


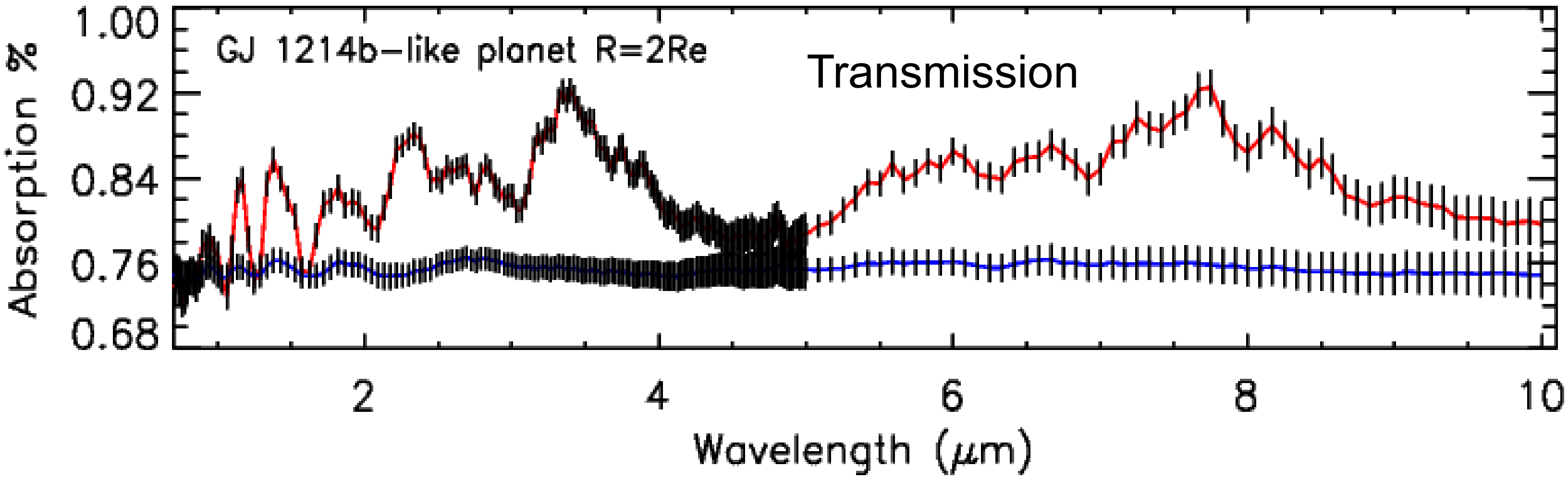
RED = metal-enhanced solar spectrum
BLUE = H2O dominated (small H)

GJ 1214b 2R_Earth with error bars

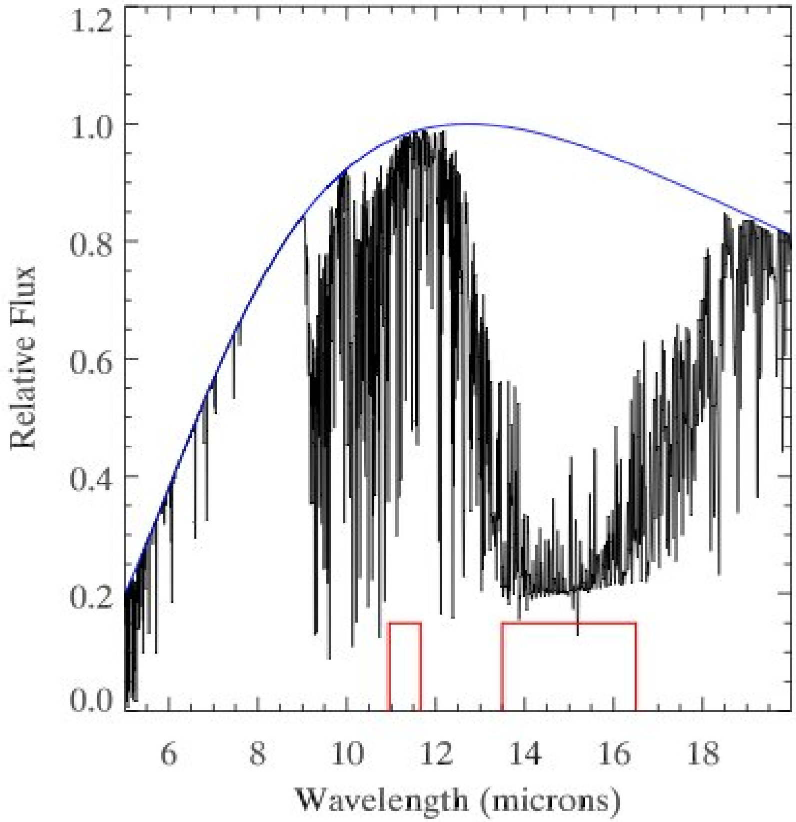
RED = metal-enhanced solar spectrum

BLUE = H2O dominated (small H)





MIRI detection of CO_2 in Super-Earths?



Deming et al. (2009) showing Miller-Ricci Super-Earth (2009) and MIRI filters

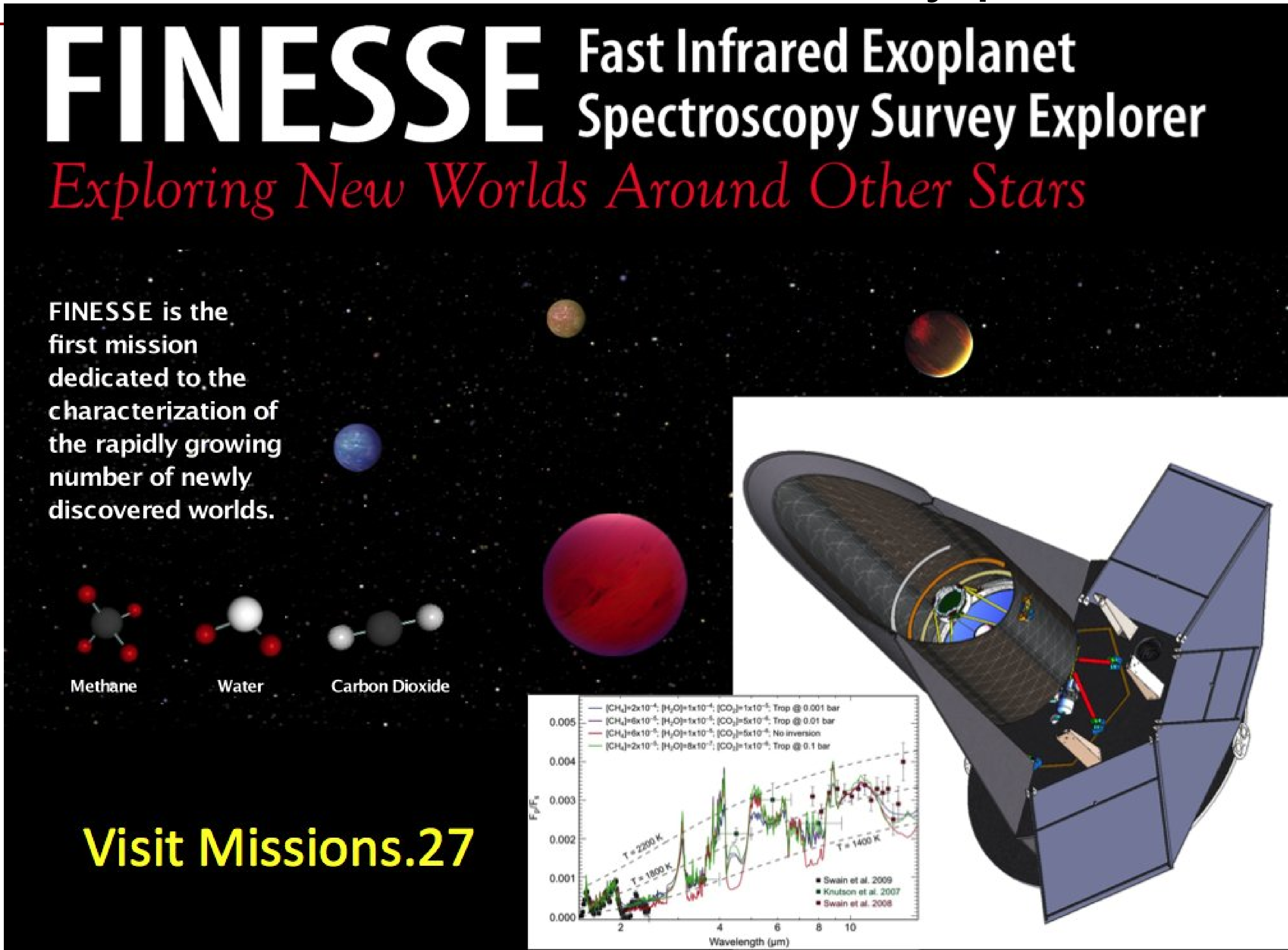
- JWST MIRI filters (red boxes, left) can be used to detect deep CO2 absorption in Super-Earth atmospheres in emission observations (Miller-Ricci 2009 model, left)
- Modelling shows that modest S/N detections possible on super-Earth planets around M stars (Deming et al. 2009).
- Could detect this feature in ~50 hr for ~300-400K 2 R_e planet around M5 star at 10 pc.

What about true Earths?

- Forget detecting spectral features in true Earth / Sun analogs (ExoPTF erratum, Kaltenegger & Traub)
  - A completely opaque feature in the Earth's atmosphere has an equivalent area of 1E-6 of Sun
- Transits of Earths around M5 stars have 10x better contrast (area ratio) than Earth around Sun
  - Detecting spectral features not likely achievable due to systematics
  - Can probably detect features in 1 R_Earth planet with H-dominated atmosphere
- We can detect the thermal emission of 2R_e planets in Hzs of M stars in mid-IR filters (15 – 20 microns) in ~4 eclipses
  - Might be able to detect 350K Earths in ~10 eclipses

How do we find the best targets?

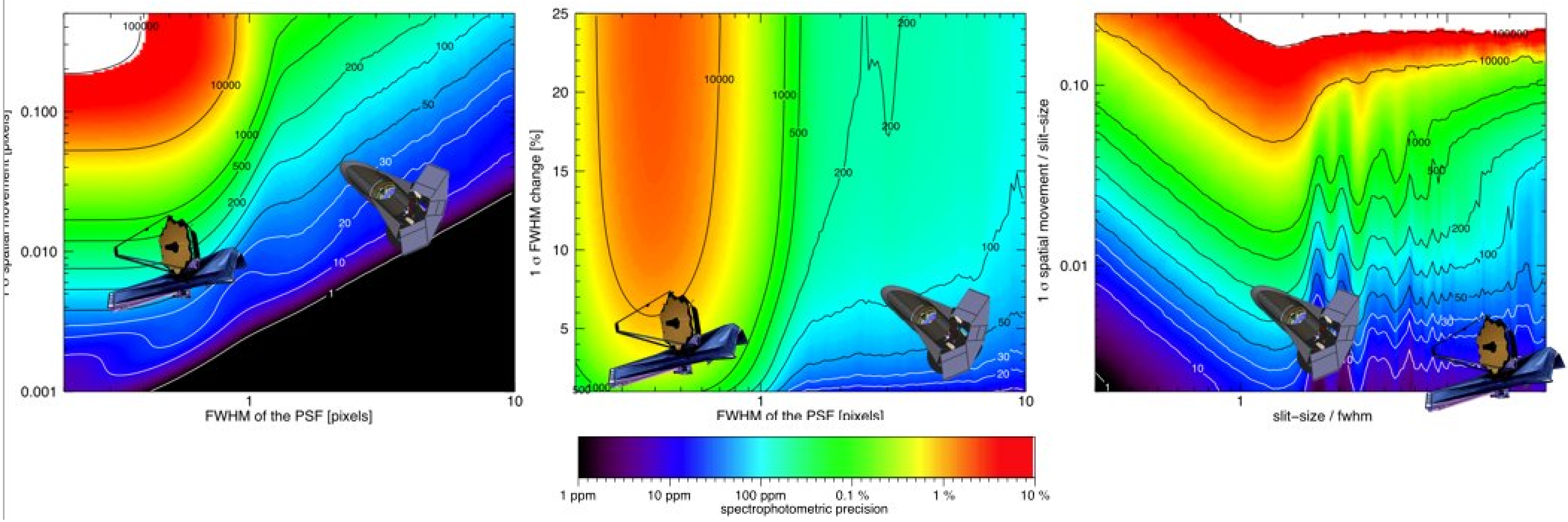
How do we characterize many planets?



FINESSE Provides Low Systematic Errors

	HST/NICMOS	Spitzer/IRS	Ground
Major systematic error	Inter and intra-pixel gain variations	slit-loss effect	Earth-atmosphere

Pointing induced gain change | Focus induced FPA change | Pointing induced slit-losses



FINESSE will provide high quality spectra of exoplanet atmospheres without processing to remove systematic noise

Note: FINESSE and JWST NIRSpec ~2 micron performance shown. Other JWST modes expected to have lower systematic errors

Some Takeaways

- Expect exquisite JWST spectra of gas giants
  - Determine abundances, temperature profiles, and energy transport in hot Jupiters with little degeneracy using transit & eclipse spectra over 0.7 – 10+ microns.
- Mid-IR spectra can identify unknown emission in Spitzer IRAC 5.8 μm band of planets with suspected hot stratospheres
- Easily constrain compositions of mini-Neptunes like GJ 1214b (down to 2 R_E and smaller)
- Possibly detect CO_2 absorption in Super-Earths
- ***We need an all-sky transit survey mission to find good planets:*** ELEKTRA (or TESS) Explorer
- Plenty of exoplanet spectroscopy to do: Ideally with both JWST and FINESSE / EchO
  - Stability and low systematics are as important as aperture